Comparison of Three-Phase Active Rectifiers For Aircraft Application

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***Abstract*—In aircraft applications, there has been an increasing trend related with the More Electric Aircraft (MEA), which results in rapid rise in the electrical power demand on-board. One of its goals lies in minimizing weight and volume of the electrical subsystem while maintaining good power quality and efficiency. The main purpose of this paper is to present and analyze an electrical design of three-phase Boost rectifier, three-phase Buck rectifier and three-phase Vienna rectifier for 10 kW active rectifiers and compare them in terms of weight, volume, efficiency etc. Moreover, the design is obliged to comply with DO-160 standard for avionic equipment with 230 V_{AC}, 360-800 Hz grid conditions. Even though all proposed solutions satisfy the standard requirements, it will be shown that the Vienna rectifier has the lowest volume and therefore, the better solution overall. However, due to increased number of semiconductors and additional circuitry required for soft start-up, the Buck rectifier would prove to be the safest solution failure-wise.**

***Index Terms*—ac-dc converter, aircraft application, boost, buck, PWM rectifier, PFC rectifier, PFC, three-phase, VIENNA Rectifier**

I. INTRODUCTION

In the ever-growing market of the civil aircraft, there has been a constant need for improvement in many fields. The improving trend is mainly oriented into replacing heavy and maintenance costly hydraulic, pneumatic and mechanical parts of the aircraft with electrical equivalents. Any part of the airborne aircraft must not fail during the duration of the flight, thus making the reliability of the equipment of the utmost importance. Moreover, the take-off weight of the aircraft is of major concern due to the increased fuel consumption. Thus, the main concerns in the aircraft the reliability, weight and volume will be the major design constraints in this work.

The conventional rectifiers employed in today aircraft are relying on the passive solutions which are extremely robust, but heavy and require tight mains regulation in order to operate within specifications [1, 2].

The twelve-pulse three-phase voltage loaded rectifier depicted in the Figure 1 is one of the typical representative of the auto-transformer based rectifiers. The basic operation of the rectifier, as well as design guidelines for the line side interphase transformer is presented in [3]. The presented rectifier provides high reliability due to the line commutating diode bridges and high efficiency due to the fact that no high-frequency switching is employed. However, apart from line filtering inductors L, the interphase transformers are key part of the rectifier which increments the weight of the rectifier. Without adding an active stage at the output [4], no control over the output voltage is possible.

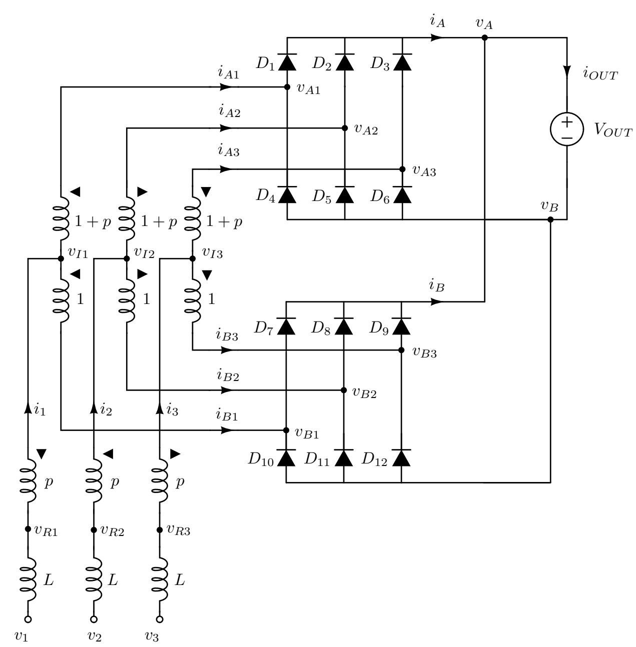

Fig. 1. The voltage loaded twelve-pulse rectifier

The active rectifiers utilize semiconductors switching at high frequencies in order to provide control to the rectifier input currents and output voltage, and provide an opportunity to reduce size of magnetic components. The reliability of the high-frequency switching devices can be argued, but with the advancements in technology, more robust and reliable switching devices are becoming available in the market. Therefore, the main accent of this paper will be on comparative study and analysis of three 10 kW three-phase active rectifiers.

II. Relevant regulations

The main standard that this avionic equipment needs to comply with is Environmental Conditions and Test Procedures for Airborne Equipment or DO-160. In it a wide spectrum of different conditions and tests are provided. Two tests were selected from DO-160F Section 16 [5] in order to compare designed active rectifiers performance with 230 V_{AC}, 360-800 Hz grid conditions.

1) Input generator unbalance test: The test procedure defined in this Subsection is related to the potential unbalance that can occur in the operation of the employed generator. In order to emulate the output impedance of the onboard generator, the inductors are placed in series with the output of the three-phase voltage source according to the standard with value of $L_g = 252\,\mu\mathrm{H}$. The test procedures from this Subsection defines unbalance of the three-phase generator both in amplitude and in phase. The voltage generated is purely sinusoidal, free of the higher order harmonics. The generator testing operating points are defined in the Table I. In the Figure 2 the test setup is described.

TABLE I
Defined test procedure for the generator unbalance test

$\underline{V}_{Ag,RMS}$ [V] [Hz]	$\underline{V}_{Bg,RMS}$ [V]	$\underline{V}_{Cg,RMS}$ [V]	f [Hz]
$248\angle 0°$	$248\angle -114°$	$230\angle 126°$	360
$248\angle 0°$	$248\angle -114°$	$230\angle 126°$	400
$248\angle 0°$	$248\angle -114°$	$230\angle 126°$	800

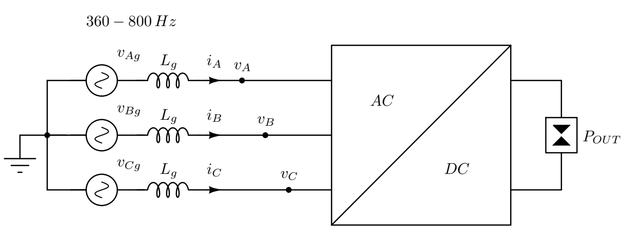

Fig. 2. The test setup for the generator unbalance test

The test procedure is passed if the rectifier power factor on each phase remains greater than 0.95 leading and greater than 0.75 lagging. Also, VA difference between the phase which delivers the most power and the one which delivers the least power must be below 590 VA.

Furthermore the current harmonic spectrum of the generator currents i_A, i_B and i_C at full load and balanced conditions needs to satisfy the limits defined by the Figure 3.

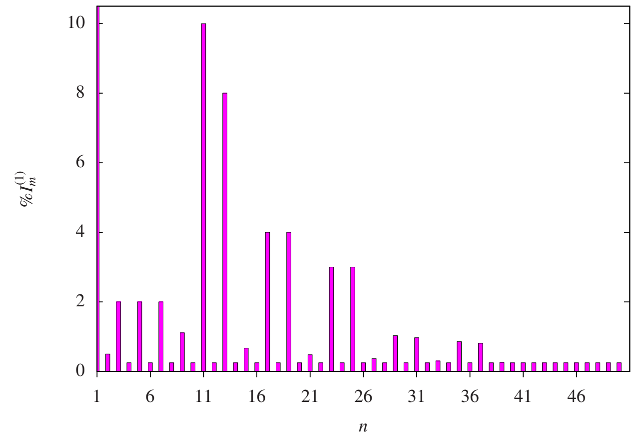

Fig. 3. The harmonic limits specified by the DO-160F

2) Input generator THDV test: The second test used for measuring performance of the rectifier is the input generator voltage total harmonic distortion (THDV) test. The test setup is presented in the Figure 4.

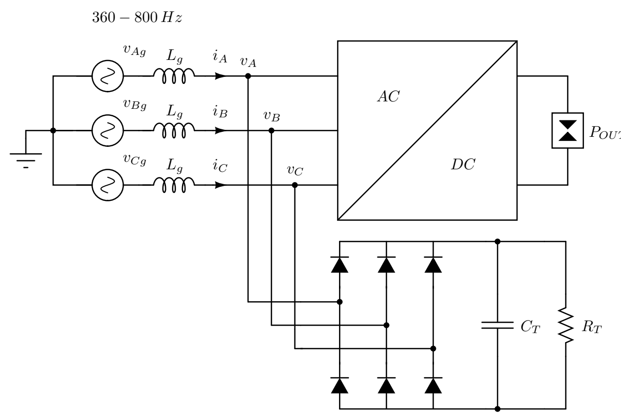

Fig. 4. The test setup for the generator THDV test

The generator in this test is balanced at nominal RMS value of 230 V. Before connecting the rectifier, a six-pulse diode bridge is connected to the generator with RC load. The output $R_T - C_T$ load is varied so that a voltage distortion at the connection points is increased to 10%. Afterwards, the rectifier is connected and starts to operate at nominal output power. The test is passed if *THD* of the voltages of the connection points v_A, v_B and v_C remains below 12%. These procedures are employed at frequencies of 360, 400 and 800 Hz.

III. Three-phase Boost Rectifier

The three-phase Boost rectifier [6–8] is presented in the Figure 5. The first main constraint of this two-level topology is that DC bus voltage needs to be sufficiently higher than maximum line to line voltage of the three-phase source. Furthermore, this converter is also bidirectional which will be reflected on superior reactive power compensation capabilities. The control of the input current quality is realized by controlling the voltage drop on the input inductors L. The presence of the inductors on the AC side implies relatively high weight due to two-level nature of the rectifier [9]. However, AC inductors are beneficial for EMI filtering capacitor size, which implies less reactive power handling by the rectifier. Additionally, this topology and its derivations require additional circuitry for the soft start-up.

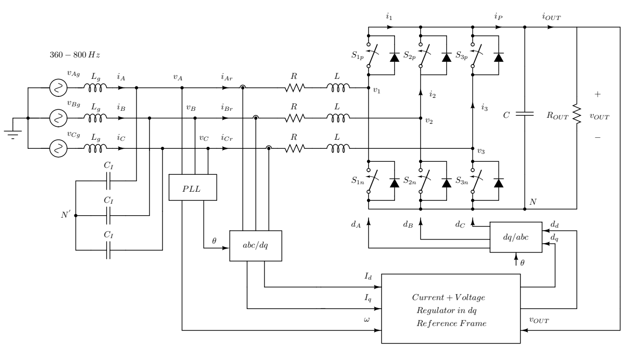

Fig. 5. Three-phase Boost Rectifier with implemented control and EMI filter

In order to control the output voltage and the input currents, adequate dq model is derived presented in the Figure 6. The control strategy consists in closing two current loops from d_d to i_d and d_q to i_q with PI regulators and an outer voltage loop closed on d subsystem.

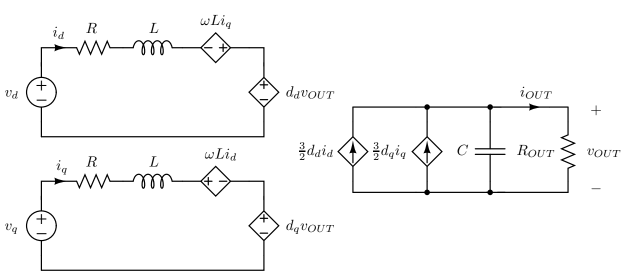

Fig. 6. dq model for Boost rectifier

General specifications for the Boost rectifier are given in the Table II.

TABLE II
THE BOOST RECTIFIER POWER STAGE PARAMETERS

$V_{Ag,RMS}$	230 V
f	360 – 800 Hz
f_{SW}	100 kHz
V_{OUT}	700 V
$L\ (R)$	340 µH (65 mΩ)
C_I	135 nF
C	400 µF
MOSFET/Diodes	CCS050M12CM2
P_{OUT}	10 kW

The input boost inductor is designed using copper foils due to the skin effect and utilizing AMCC25 amorphous core. The inductor design overview as well as the breakdown of the losses in the rectifier semiconductors is presented in the Tables III and IV respectively.

TABLE III
THE BOOST INDUCTOR DESIGN PARAMETERS

N	23
l_g	0.5 + 0.5 mm
w_{Cu}	20 mm
t_{Cu}	0.5 mm
P_{Cu}	4 W
P_{Fe}	11 W
m_{Cu}	130 g
m_{Fe}	370 g
$L\ (R)$	340 µH (65 mΩ)

TABLE IV
BREAKDOWN OF SEMICONDUCTOR LOSSES FOR THE BOOST RECTIFIER

	MOSFET	Diode
P_{CND} [W]	0.7	7
P_{SW} [W]	39	0
P_{SW+CND} [W]	40	7
P_{TOT} [W]	282	

All previous results are presented for 10 kW output power and 400 Hz input line frequency. The efficiency of the rectifier can be estimated to 96.8 % with total volume of reactive components of 0.65 dm^3.

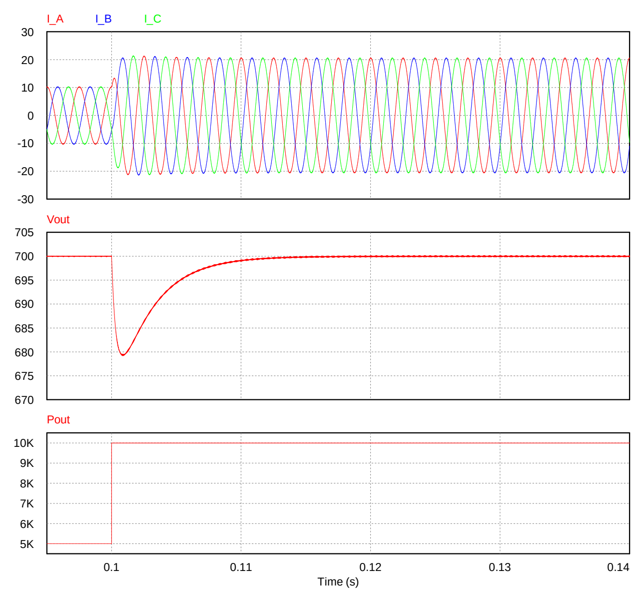

Fig. 7. Power step up at 400 Hz for Boost rectifier

TABLE V
RESULTS OF UNBALANCE TEST FOR THE BOOST RECTIFIER

f [Hz]	Phase	PF [%]	P [kW]	$\%P_{\mathrm{TOT}}$	$\Delta P_{\max}$	Pass/fail
360	A	99.71	3.47	34.6	313	Pass
	B	99.84	3.40	33.9		
	C	99.91	3.16	31.5		
400	A	99.72	3.47	34.6	315	Pass
	B	99.84	3.40	33.9		
	C	99.92	3.16	31.5		
800	A	99.78	3.49	34.8	311	Pass
	B	99.84	3.37	33.6		
	C	99.93	3.18	31.6		

TABLE VI
RESULTS OF THDV TEST FOR THE BOOST RECTIFIER

f [Hz]	Phase	THDV	Pass/Fail
360	A	9.98	Pass
	B	10.02	
	C	9.97	
400	A	10.01	Pass
	B	10.02	
	C	10.02	
800	A	10.46	Pass
	B	10.64	
	C	10.27	

IV. THREE-PHASE BUCK RECTIFIER

The three-phase Buck rectifier [10–12] is presented in the Figure 8. The first main constraint of this topology is that DC bus voltage needs to be sufficiently lower than maximum line to line voltage of the three-phase source. Due to the presence of the series diodes, this topology has unidirectional power flow which will restrict the amount of reactive power that can be handled by the rectifier. Basic operation of the rectifier consists in driving the switches in such a way so that generated sinusoidal fundamental phase currents at the input are in phase with the corresponding phase voltages. The generation of currents at AC side utilizes DC link inductor current along with current Space Vector Modulation (SVM). The main advantage of this rectifier topology is that inductive filtering is moved to the DC side and thus provides the ability to reduce weight of the inductor with respect to the Boost case. Moreover, this rectifier is not as sensitive as the boost to the shoot through failure of the leg. Also, soft start circuitry is not needed. However, it requires relatively large input capacitors which will further diminish the reactive power handling of the converter.

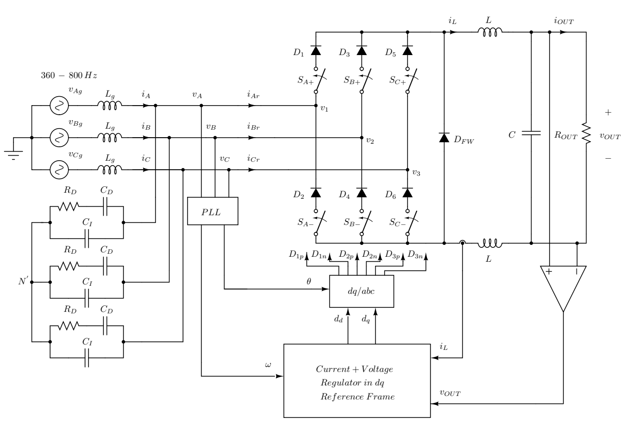

Fig. 8. The Three-phase Buck Rectifier with implemented control and EMI filter

The equivalent dq model obtained is presented in the Figure 9. The inner faster current loop is closed from d_d to i_L and outer voltage loop on d subsystem.

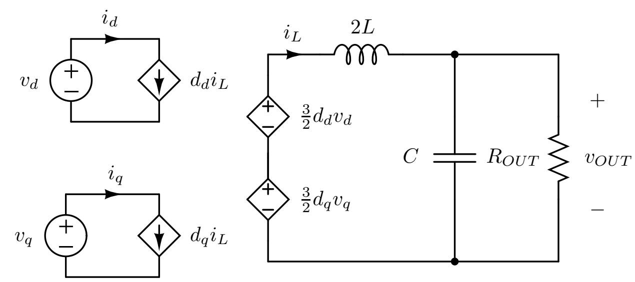

Fig. 9. The equivalent circuit of the Buck rectifier in dq domain

General specification for the Buck rectifier are given in the Table VII.

The output inductor is designed using AWG 10 wires due to dominant DC component compared to switching frequency harmonic components and utilizing AMCC25 amorphous core. The inductor design overview as well as the breakdown of the losses in the rectifier semiconductors is presented in the Tables VIII and IX respectively.

TABLE VII
THE BUCK RECTIFIER POWER STAGE PARAMETERS

$V_{Ag,RMS}$	230 V
f	360 – 800 Hz
f_{SW}	100 kHz
V_{OUT}	400 V
L (R)	200 µH (18 mΩ)
C_I	1.98 µF
C_D	0.9 µF
R_D	30 Ω
C	400 µF
MOSFET	2 x SCT30N120
HF Diode	2 x STTH6012
FW Diode	(2 + 2) x SDP30S120
P_{OUT}	10 kW

TABLE VIII
THE BUCK INDUCTOR DESIGN PARAMETERS

N	20
l_g	0.45 + 0.45 mm
P_{Cu}	6 W
P_{Fe}	6 W
m_{Cu}	100 g
m_{Fe}	370 g
L (R)	200 µH (18 mΩ)

TABLE IX
BREAKDOWN OF SEMICONDUCTOR LOSSES FOR THE BUCK RECTIFIER

	MOSFET	HF Diode	FW Diode
P_{SW+CND} [W]	12 x 5	12 x 6	4 x 6
P_{TOT} [W]	156		

All previous results are presented for 10 kW output power and 400 Hz input line frequency. The efficiency of the rectifier can be estimated to 97.9 % with total volume of reactive components of 1.2 dm^3 and losses in the damping resistors [13] of 30 W.

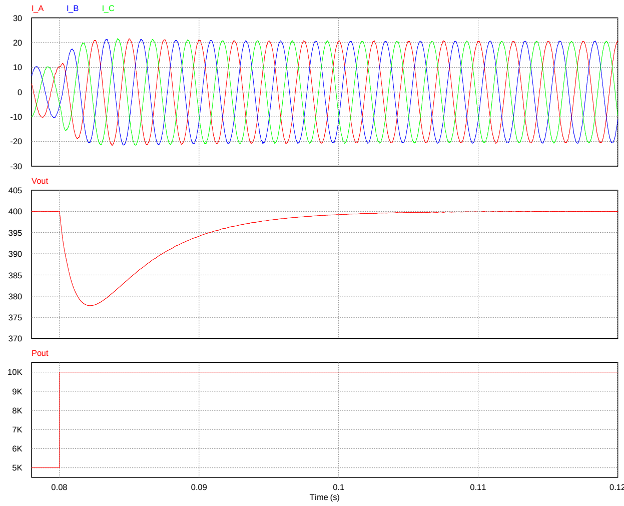

Fig. 10. Power step up at 400 Hz for Buck rectifier

TABLE X
RESULTS OF UNBALANCE TEST FOR THE BUCK RECTIFIER

f [Hz]	Phase	PF [%]	P [kW]	$\%P_{\mathrm{TOT}}$	$\Delta P_{\max}$	Pass/fail
360	A B C	99.73 99.76 99.82	3.44 3.43 3.13	34.4 34.3 31.3	312	Pass
400	A B C	99.73 99.74 99.81	3.45 3.43 3.13	34.5 34.3 31.2	323	Pass
800	A B C	99.72 99.22 99.81	3.60 3.36 3.07	35.8 33.6 30.6	532	Pass

TABLE XI
RESULTS OF THE THDV TEST FOR THE BUCK RECTIFIER

f [Hz]	Phase	THDV	Pass/Fail
360	A B C	11.14 11.18 11.26	Pass
400	A B C	11.22 11.08 11.10	Pass
800	A B C	10.24 10.34 10.20	Pass

V. THREE-PHASE VIENNA RECTIFIER

The three-phase Vienna rectifier [14–16] is presented in the Figure 11. The Vienna rectifier keeps all general advantages with the respect to the Boost rectifier with exception that it is unidirectional converter which implies limitations regarding reactive power handling. However, due to the presence of the inductor on the AC side the EMI capacitor needed to comply with the harmonic requirements is small. Moreover, this rectifier is by nature three-level converter which allows smaller values of input inductance.

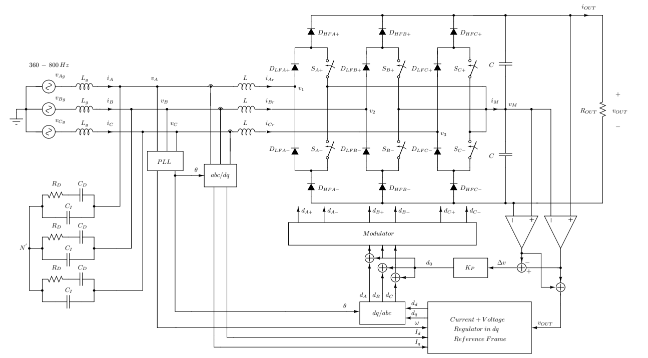

Fig. 11. Three-phase Vienna Rectifier with implemented control and EMI filter

The derived dq model is presented in the Figure 12. The control strategy is the same as for the Boost rectifier, with the exception of additional control loop for output capacitor voltage balancing.

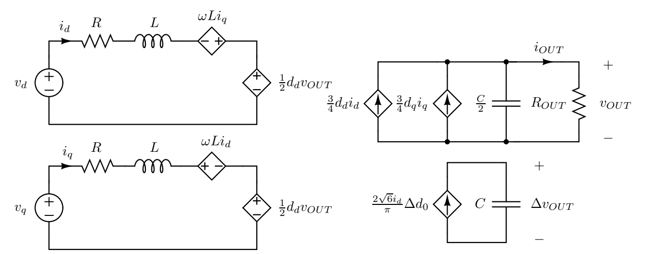

Fig. 12. dq model for Vienna rectifier

General specifications for the Vienna rectifier are given in the Table XII.

TABLE XII
THE VIENNA RECTIFIER POWER STAGE PARAMETERS

$V_{Ag,RMS}$	230 V
f	360 – 800 Hz
f_{SW}	100 kHz
V_{OUT}	800 V
L (R)	200 µH (50 mΩ)
C_I	88 nF
C_D	88 nF
R_D	30 Ω
C	200 µF
MOSFET	IPW60R160C6
HF Diode	2 x C3D20060D
LF Diode	VS – 40EPS12PBF
P_{OUT}	10 kW

The input boost inductor is designed using same technology like in the Boost case with smaller core AMCC10. The inductor design overview as well as the breakdown of the losses in the rectifier semiconductors is presented in the Tables XIII and XIV respectively.

TABLE XIII
THE VIENNA INDUCTOR DESIGN PARAMETERS

N	23
l_g	0.7+0.7 mm
w_{Cu}	10 mm
t_{Cu}	0.5 mm
P_{Cu}	3 W
P_{Fe}	9 W
m_{Cu}	70 g
m_{Fe}	198 g
L (R)	200 µH (50 mΩ)

TABLE XIV
BREAKDOWN OF SEMICONDUCTOR LOSSES FOR THE VIENNA RECTIFIER

	MOSFET	HF Diode	LF Diode
P_{CND} [W]	9.7	6.25	5
P_{SW} [W]	11.5	0	0
P_{SW+CND} [W]	21.2	6.25	5
P_{TOT} [W]	233		

All previous results are presented for 10 kW output power and 400 Hz input line frequency. The efficiency of the rectifier can be estimated to 97.4 % with total volume of reactive components of 0.6 dm^3 and losses in the damping resistors of 1 W.

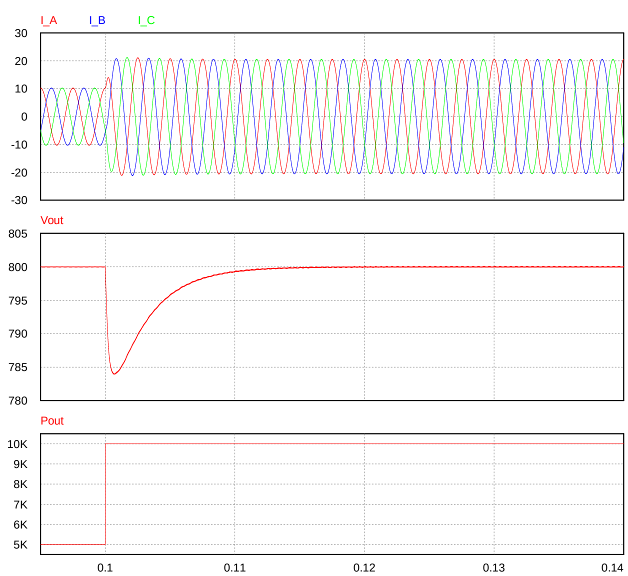

Fig. 13. Power step up at 400 Hz for Vienna rectifier

TABLE XV
RESULTS OF UNBALANCE TEST FOR THE VIENNA RECTIFIER

f [Hz]	Phase	PF [%]	P [kW]	$\%P_{\mathrm{TOT}}$	$\Delta P_{\max}$	Pass/fail
360	A	99.73	3.48	34.7	342	Pass
	B	99.78	3.41	34		
	C	99.90	3.14	31.3		
400	A	99.74	3.49	34.8	348	Pass
	B	99.77	3.40	33.9		
	C	99.91	3.14	31.3		
800	A	99.86	3.52	35.1	344	Pass
	B	99.74	3.34	33.3		
	C	99.93	3.17	31.6		

TABLE XVI
RESULTS OF THE THDV TEST FOR THE VIENNA RECTIFIER

f [Hz]	Phase	THDV	Pass/Fail
360	A	9.22	Pass
	B	9.23	
	C	9.23	
400	A	9.00	Pass
	B	9.00	
	C	9.00	
800	A	7.29	Pass
	B	7.29	
	C	7.24	

VI. COMPARISON AND CONCLUSION

The analysis of three-phase Boost rectifier, three-phase Buck rectifier and three-phase Vienna rectifier for 10 kW avionic application has been performed. The efficiencies, magnetics weight and reactive components volumes has been provided, as well as simulation results demonstrating transient behavior of the rectifiers. The presented active rectifiers all exhibit compliance with the DO160-F tests provided in the Section II. Moreover, the three converters have similar efficiencies. However, Buck rectifier has bigger volume compared to the Boost and Vienna topologies. This is due to the fact that input currents of the Buck are discontinuous and require higher EMI filtering effort. As expected, Buck rectifier proves to be superior in terms of magnetics weight because filtering inductor is located on the DC side instead of AC. However, Vienna rectifer 3-level nature benefits the magnetics weight and makes it a competitive solution. The Boost rectifier has the advantage of modulation simplicity and huge reactive power handling capabilities due to its bidirectional nature. However, it is fault intolerant to shoot-through failures in the semiconductors and specifically for this application bidirectional power flow is forbidden. Furthermore, Boost and Vienna solutions require additional circuitry for start-up. Lastly, of the two unidirectional converters, Vienna shows slightly lower minimum power level P_{min} at which it can obtain unity power factor due to smaller input EMI capacitors.

Even though the Vienna rectifier based on results presented in the Tables XVII and XVIII proves to be the best option overall, due to high number of semiconductors and vulnerability to certain failures which are not analyzed in this paper and require additional protection circuitry, the Buck rectifier would prove to be most fitting for this application.

TABLE XVII
PRIMARY COMPARISON PARAMETERS

Topology	V [dm^3]	m [kg]	η [%]
Boost	0.65	1.5	96.8
Buck	1.2	0.9	97.9
Vienna	0.60	0.8	97.4

TABLE XVIII
SECONDARY COMPARISON PARAMETERS

Topology	EMI size	P_{min} [kW]	Start-up circuit	Control
Boost	Small	0	Needed	Simple
Buck	Large	3	Not needed	Moderate
Vienna	Small	2.5	Needed	Complex

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